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Emerging Territories of Digital Material Practice

Cristina Nan, Charlie Patterson, and Remo Pedreschi

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Emerging Territories of Digital Material Practice

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Keywords: textile formwork; fabric cast concrete; textile 3D printing; digital crafting; digital fabrication

Abstract: This paper explores the emerging future field of fabric form work for concrete structures in combination with 3D printing. The showcased material experimentations represent studies which focus on the simultaneous use of fabric formwork and textile 3D printing in order to create a new type of material process for forming and fabricating non-standard geometries applied to architectural elements. Textiles in combination with 3D printed patterning are seen in this context as tools for form generation and to a certain extent also for form control.

This practice-based research offers a new alternative to predominant fabrication methods for complex geometries, showcasing the benefits

of hybrid digital crafting techniques. The developed manufacturing strategy will be explained through a series of material experimentations and resulting prototypes. The following studies investigate fabrication processes and surface texturing methods for the manufacturing of small and large-scale prototypes such as tiles or concrete columns. The studies represent material investigations with a hybrid material system —textile, concrete and 3D printed silicone— and are process driven, concentrating more on process experimentation —seen as a digital crafting methodology— rather than focussing on a predefined design output.





Introduction

Today's architectural practice shows an ongoing preoccupation with the generation and thus also fabrication of non-standard geometries. Through the intensive digitalisation which occurred throughout the last three decades, digital form generation of complex geometries does not represent a challenge for the discipline anymore. Through the means of digital analysis and simulation, geometrical challenges emerging from complex curvature can be handled with relative ease, while the fabrication of such structures still shows — in most cases— an unbalanced ratio between costs and benefit. The fabrication of complex geometries involves the development of equally complex frameworks, moulds or the use of advanced digital fabrication technologies. The starting point of this research lies in developing an innovative process for the fabrication of non-standard geometries with concrete, by minimising the needed framework and facilitating the efficient manufacturing of a variety of complex shapes. The research focuses on the development of a new material process, correlating material, technology and technique as part of a reinterpretation of architectural material practice.

Concrete was chosen as the base material as it represents one of the most commonly used construction materials of our age. One of the main advantages in using concrete consists in its performance characteristics, structural capacity, durability and very importantly, in the context of

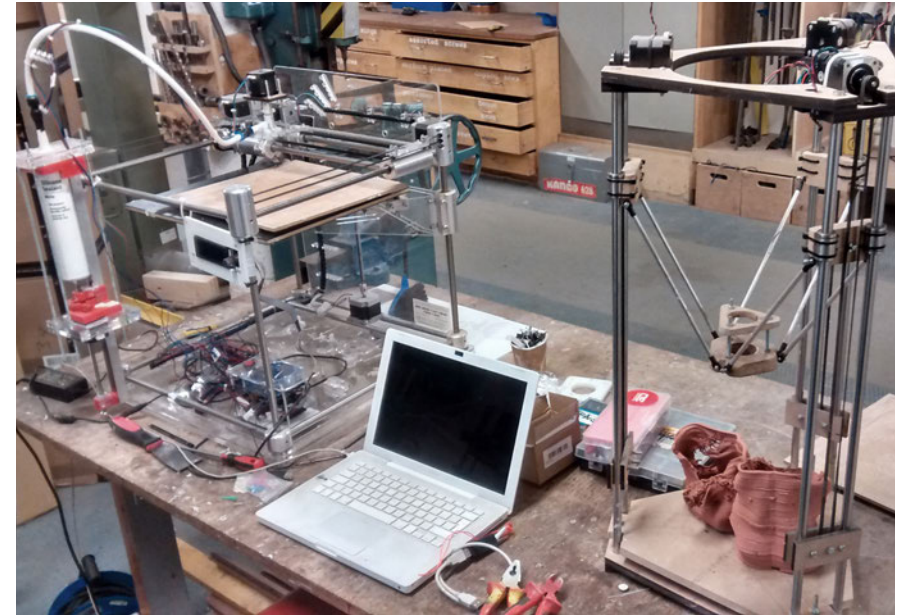


Figure 1. Hacked 3D printer for silicone and Delta Printer for clay, connected to laptop. Photo: Charlie Patterson.

complex geometries, its ability to be moulded or cast into a wide range of shapes. Casting concrete, by using material intensive wooden or rubber moulds, can be seen as traditional craft, which has been subject to limited changes in the course of time. The intention of this research lies in advancing this traditional manufacturing process by developing a hybrid digital crafting method and strategy based on combining fabric formwork and textile 3D printing. By making use of the emerging open source culture of the maker community — for developing and adapting a self-built 3D printer— and using computational design methods a predominantly traditional crafting technique was transformed into a digital crafting method and a new type of material system was developed.



Fabric Cast Concrete

One traditional fabrication method for non-standard geometries which offers a viable solution in terms of time and cost effectiveness is fabric formed concrete. The technique is described as follows by Veenendaal (2011, p. 164):

“Fabric formwork is a building technology that involves the use of structural membranes as the main facing material for concrete moulds. Unlike traditional formwork, the material is highly flexible and can deflect under the pressure of fresh concrete. The resulting forms exhibit curvature as well as excellent surface finishes that are generally not associated with concrete structures.”

Originating in the Industrial Revolution, this technique looks back on a long application history throughout architecture and engineering, from Gustav Lilientahl to James Waller and Miguel Fisac, to name only a few. (Veenendaal, West 2011) While textile formwork does not represent an unexplored field, compared to the traditional way of casting concrete, it still has experienced only a limited amount of practical use for large scale projects, although showing a number of significant advantages. (Veenendaal, Coenders 2011). Compared to wooden formwork for concrete casting, textile formwork offers a series of benefits, specially when used for the fabrication of non-standard geometries. One of the main advantages would be that fabric formwork is less material, cost



Figure 2. Twisted column. Fabric formwork and wooden structure, before and after the concrete casting of a twisted column. Prior to the casting, the fabric has to firmly stretched. The inside of the fabric formwork contains a 3D printed patterning, used for influencing both the surface texture of the concrete and the stretching behaviour of the fabric. Photo: Cristina Nan.



and time intensive, what assembly of the formwork itself is concerned, compared to wooden or metal formwork. Using less material for the formwork, implies a simultaneous reduction of waste material. Its lightweight implies easier manipulation and handling. Additionally, by applying different tailoring techniques a wide range of complex geometries can be easily achieved, by using gravity as one of the main parameters in terms of form finding (Pedreschi, 2008). Other significant advantages from a structural point of view are an increased surface strength, a higher surface density which leads to an improved resistance to freezing and thawing and better control over surface irregularities, increasing the durability performance of the built structure (Malone, 1999).

In the context of the presented research, one of the central advantages of working with fabric cast work are the openness of the process, in terms of form finding, the process of prototyping and the development of the fabrication strategy itself, combining an analogue fabrication technique with a digital technology such as 3D printing. Another beneficial aspect of conducting experiments with textile formwork lies in the fact the it necessitates a direct interaction of the maker with the material, leading to a better understanding of the underlying process parameters and ways of manipulating them (Chandler, 2007).



Figure 3. Twisted column. Photo: Charlie Patterson.



3D Printing

During the last years 3D printing has become a main stream technology, available to and used by professionals as well as non-professionals alike. As a widely accessible rapid prototyping technology, it has been embraced by the architectural discipline, beyond its use as a tool for model building. Mainly in the academic field, vast research studies have been undertaken in order to implement the technology in the construction area. As 3D printing represents an additive manufacturing technology based on fabricating an object by depositing material in consecutive layers, using data deriving from a digital model, it holds the potential of offering a new fabrication strategy for complex geometries based on curvature, by also making the need of complex substructures futile. (Gibson, 2015) Some of the leading researchers investigating this layer-based approach of building are Neri Oxman at the MIT MediaLab or Behrokh Khoshnevis at the University of Southern California. The difficulty and fundamental problem these research endeavours are facing, is the scaling up of the technology, meaning how to scale up the 3D printer in order to be able to print large scale objects, bigger than the printer itself. In order to facilitate this, Khoshnevis extracted the layer-based principle of 3D printing and applies it to mobile robotic arms. The printing is thus done by industrial robot arms, which can print any type of structure bigger than themselves (Khoshnevis, 2004).

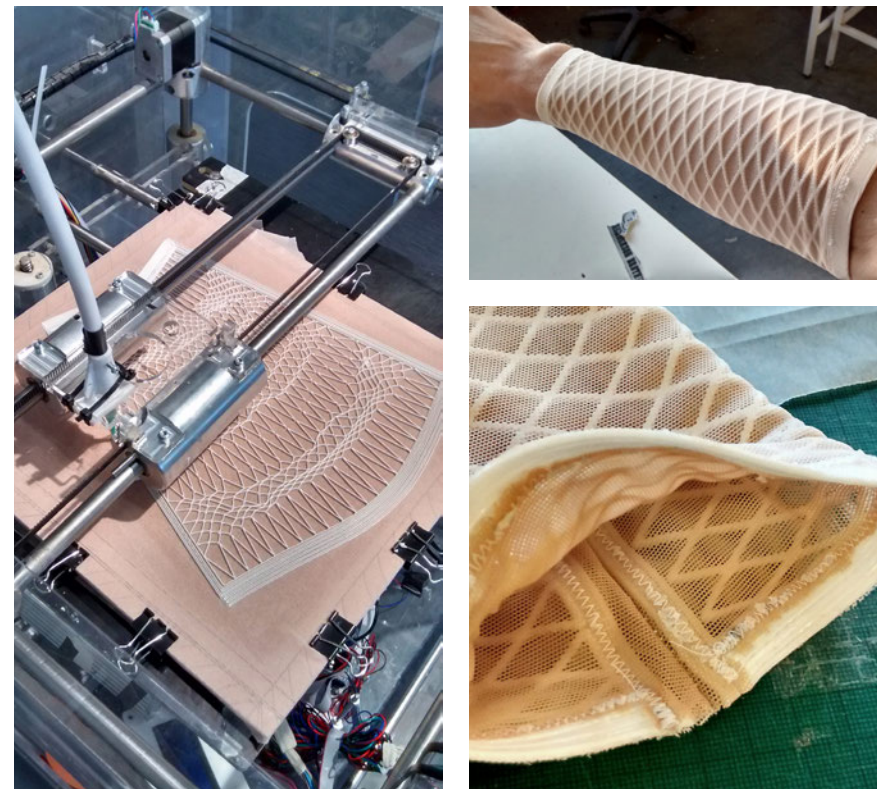


Figure 4. Silicon 3D printer, printing customised compression pattern. Compression braces and detail of patterned silicon layers. Photo credit: Charlie Patterson.

A relevant aspect of this initial experimentation phase was the understanding of the printed patterning and how the fabric reacts to specific printed pattern designs.

Other than these approaches to 3D printing, the here showcased studies make use of this technology as an extension and enhancement to an existing, traditional, analogue technique — casting concrete. Additive manufacturing is viewed in this context as an additional element of a hybrid fabrication chain.



The main objective of making use of 3D printing technology for this experimentation series, is to fabricate 3D printed patterns on a fabric substrate, in order to manipulate and control form generation and geometry.

Hacked 3D printer

For the purpose of this research an open source 3D printer was hacked, which was then used for printing with extruded silicone directly on fabric. Using open source machine templates for the printer offered the possibility of customising the nozzle and the extrusion system for a specific material —in this case silicone. Instead of printing directly onto the print bed, the material depositing is taking place on textile. The fabric is fed through over the bed horizontally, allowing printing of long runs of textile. A repetier host was used to then the g-code —data of the printing path— to the printer, allowing for live control of the material flow and print speed. During the testing of the printer, it was found that larger surface areas could be deposited with a higher printing speed without any loss of quality, whereas taller and narrower element patterns, such as the vertical fins in the twisted column, need to be printed slower, as to ensure a high printing quality of the top edge.



Figure 5. Concrete Panel. Rectangular tile featuring printed disrupted design grid. Photo: Charlie Patterson.

Material experimentations

The following material research combines experimentation with fabric cast concrete, silicone 3D printing with a hacked, open source 3D printer and traditional tailoring technique for stitching the fabric formwork. The design and fabrication processes will be described in detail, while it is important to note that only through the coordinated advancement of craft, skill based knowledge, material behaviour and building own custom tools —hacked silicone 3D printer— the described customised prototypes could be developed.

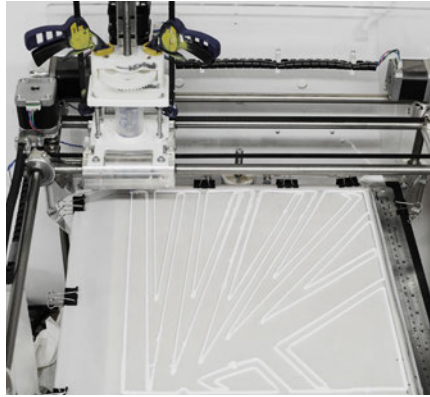


Figure 6. Waisted Column. Manufacturing process, from casting to removing the fabric formwork. Photo: Cristina Nan and Charlie Patterson.

Medical Gloves and Compression Braces

The following material research combines experimentation with fabric cast concrete, silicone 3D printing with a hacked, open source 3D printer and traditional tailoring technique for stitching the fabric formwork.

In a first step, the initial experimentation focused on the assembly and development of the silicone 3D printer itself. Besides the technical aspects of the printing process, the concept of 'physically programming



Figure 7. Waisted Column. Manufacturing process, from casting to removing the fabric formwork. Photo: Cristina Nan and Charlie Patterson.



the textiles' was developed. This concept or strategy refers to using the printed silicone to alter the stretching behaviour of the fabric. Depending on the chosen printing pattern different manipulations of the textile behaviour can be achieved. Silicone was adopted as a material for the printing and for further experiments due to its homogeneity, which corresponds to industrial standards, its inherent elasticity, easy availability and the low cost of the material. The first tests have been conducted by printing with silicone on nylon fabric and resulted in the manufacturing of prototypes of customised medical compression braces and gloves. Through the pattern design and the material interaction between the printed silicone and the textile the ergonomic behaviour of the braces and gloves could be enhanced. Patterning and stretching behaviour became the main design and fabrication parameters. In order to obtain working prototypes a precise calibration of material and machine parameters was necessary, thus enabling the maker to obtain an increased control over both design and fabrication process (Nan, 2016).

This first phase of the research has led to a profound understanding of how to efficiently control and manipulate the extrusion speed, extrusion rate and the flow of the silicone, so that the printed layers reached a high definition. This approach showcases how a new type of both material practice and culture were achieved, by correlating the materials, their material behaviour, design and fabrication strategy to the specific machine configuration. To conclude, a relevant aspect of



Figure 8. Twisted Column. Manufacturing process, from casting to removing the fabric formwork. Photo: Charlie Patterson.



Figure 9. Twisted Column. Removal of the fabric formwork with 3D printed patterning. Photo: Cristina Nan.

this initial experimentation phase was the understanding of the printed patterning and how the fabric reacts to specific printed pattern designs. This accumulated tacit knowledge was then applied for the digital crafting process of concrete prototypes.

Concrete Panel

The next research phase engaged with fabric cast concrete. Prior to the creation of large-scale columns rectangular panels were cast, featuring a 3D printed disrupted grid design. For this specific case the patterning of the printed silicone served only as a tool for surface ornamentation, resulting in an aesthetic expression of the surface texture. Being a soft, flexible and water repellent material, the silicone allowed for

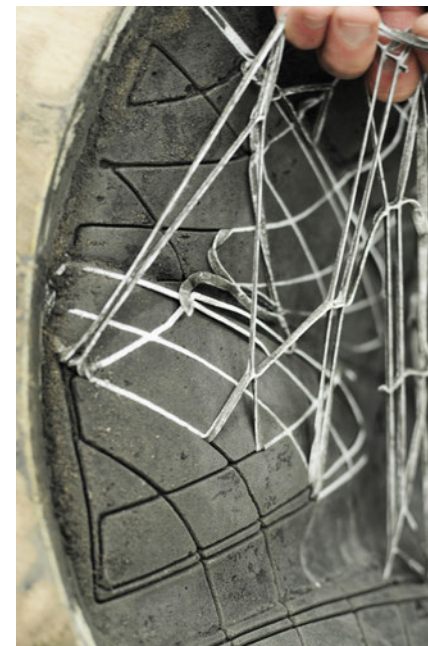


Figure 10. Cone. Removal of the 3D printed patterning from the inner shell of the cone. Photo: Cristina Nan and Charlie Patterson.



Figure 11. Cone. Fabric formwork with 3D printed patterning, partially stitched together. Photo: Cristina Nan.

precise detail to be taken by the surface. The resulting detail and its unexpected high resolution served as inspiration for the further work, regarding the achieved material aesthetic.

The material interaction between the silicon and concrete proved to be unproblematic, regarding the casting itself and the subsequent removal of the silicone pattern design, after the curing of the concrete. Through a series of material experimentation

Fabric Cast Columns

The next material iterations were focused on fabricating large scale architectural elements, such as columns. For this series of experiments



Figure 12. Material mixture for fabric cast cone. Black powder pigment was added to the aggregate, sand and cement mixture. Photo: Cristina Nan.

a neutral cure silicone was used, due to its durability, flexibility and good layer control during the printing process. The initial design for all columns was produced with the 3D modelling software Rhino, while the g-code — the data for the printing path—for the printer was created with Silkworm, a plugin for Grasshopper, a graphical algorithm editor integrated in Rhino. This kept the data flow within a single program and facilitate a better control over the digital processes. The digital crafting process was continuously refined over the course of the production of the columns, incorporating further understanding of the form generation process to allow a better integration of material parameters.

Waisted Column

For the formwork of this design simple cotton fabric with no stretch was used. The columns height is 825mm and corresponds to the width of 3 print beds. When unrolled, the surface net of the column is doubly curved. In order to facilitate the stitching for a double curved geometry, the net was split into four pieces and printed in double sections. The



printed silicone and its patterning were used to alter the stretching behaviour of the textile, generating a selective restraint. For obtaining this effect, the printed silicone bands were given an increased height of 6mm. The silicon patterning influencing the stretching behaviour of the fabric served as one of the main form finding parameters. As the print head retraction function has a certain degree of imprecision or tolerance, travel lines for the print head are carefully planned in order to not interfere with the main design of the patterning. These can be subsequently removed from the textile with a razor blade once the silicone has cured. The used material for the casting is based on a mixing ratio of 3:2:1, for white aggregate, sharp sand and white portland cement. The silicon provides a unique way to also add a distinct surface detailing. Achieving this type of material expression of the surface texture would be both time consuming and costly to replicate with conventional formwork.

Twisted Column

The second column to be cast was the twisted column. Also for this design, the varying vertical printed silicon layers and the horizontal 'silicon ties' are used to control the stretching behaviour of the textile and thus to manipulate the geometric control of the form. For the twisted column, with its height of 825mm, a different type of textile was used. A jersey fabric with a two way stretch was used for the printing. As the textile stretches significantly more in the vertical direction than



Figure 13. Fabric cast cone. Photo: Charlie Patterson.

in the horizontal, the design was orientated to take advantage of this stretching behaviour as the column is twisted. From early tests with a scaled model and sand, the observation was made that without restraint through 3D printed silicon patterning, there would be significant bulging at the base of the column due to the weight of the concrete interacting with the stretchable textile, which would considerably distort the final column. The horizontal 'ties' were printed according to the restraint at different sections of the column. The lowest section features 'ties' with



the largest surface area, in order to control the bulging at the base, where the weight of the concrete would have the highest impact. In contrast to this, the upper two sections feature progressively fewer ties of a smaller surface area, meaning that the bulging can be controlled with less silicone.

Concrete Cone

The main objective driving the third material experiment was based on exploring how fabric formwork can be deployed to create thin shells and how silicone patterning can enhance and add further complexity to the process. The textile mould consists of a 330mm high and 200 by 600mm wide cone, with a smaller cone offset by 30mm to the interior. The patterning was only printed onto the interior cone fabric. Other than in the case of the prior material iterations, the patterning reflects the digitally simulated stress lines of the structure. Stress lines depict the graphic representation of the internal forces and their direction through the surface of a specific structure. These were created using the plugin Karamba, a parametric structural analysis tool, based on finite element calculations. Also this case study showcases the advantage of fabric formwork compared to traditional formwork, in that the complex double curvature is created upon the tensioning of the fabric, rather than using a CNC hard formwork.

While the previous casting procedures have been unproblematic, the casting of the double shell has proven more difficult. The even distribution of the wet concrete mixture was rather laborious, due to the difficult accessibility of the fabric mould—in certain areas neighbouring the wooden frame—for pouring the material. This newly gained knowledge will be considered as both a design and fabrication parameter for future iterations, as a non-uniform distribution of the material leads to geometric deformations of the design and to a reduced structural stability.

Conclusions

The described material, design and manufacturing processes display the possibilities and potential arising from combining analogue and digital techniques. The merging of these two sets of approaches can lead to a new way of understanding materiality and material practice itself. Beyond emerging new process types, unexplored form aesthetics and ornamental expressions can be created.

This series of experiments, starting with small scale elements—exploring a wide range of research fields, from ergonomic optimisation, to designing digital crafting processes and exploring textural ornamentation—and leading to the fabrication of large scale concrete columns, showcases



how a digital, craft and skill based knowledge can be generated. As the research development was done through multiple digital and material iterations, by simultaneously correlating five main parameters —material behaviour, pattern geometry, fabrication process and machine— the value of experimental prototyping in architectural research became clear, in terms of advancing established process applications.

This research series showcases the resulting potential of combining traditional and customary methods with the emerging field of digital fabrication. This combination of the analogue with the digital can be executed in different manners, from the introduction of digital tools of analysis and simulation used in order to achieve optimisation to using digital form finding tools leading to focussing purely of form aesthetics. The value of the resulting outcome, whether it be an architectural component or architecture as a building entity, does not necessarily consist in the innovation level of the singular elements, but in the emerging qualities of the output. As mentioned in the introduction, fabric cast concrete represents an established field in both engineering and architecture. On the other hand, 3D printing has been embraced by the architectural practice and new ways of implementation are being explored by both research labs and practices. The open source culture and the maker movement offer for the designer or architect a new accessibility to hack existing machines and to adapt them to specific project requirements. Only by making use of open source resources was

it possible to modify a 3D printer in order to use it for silicone printing on textiles. This permits the exploration of related disciplinary fields and the development of hybrid experiments.

The interaction between digital technologies and fabric form work seen a hybrid system can find different articulations. A relevant case study to be mentioned in this context is the P-Wall experimental series designed by the design studio Matsys and its studio leader Andrew Kudless: through the means of digital iterations the elasticity of the fabric form work is being controlled by selectively restraining it, thus resulting in a set of aesthetically self-similar panels, which are being assembled to a continuous wall element. This represents a different approach compared to the here described series and demonstrates the inherent variability and adaptability of the digital. Several other investigative approaches can be named such as the work of Ron Culver and Joseph Sarafian developed at the University of California, where industrial robotic arms which pull the flexible formwork sideways are being used to simultaneously facilitate an easier pouring and distribution of the concrete and to also define the geometry of the singular component, depending on the amount of applied tension on the fabric. Neither the use of industrial robotic arms nor the flexible formwork itself represent innovative technologies — the resulting synergy is the innovation as the whole is greater than the sum of its parts. The result are new processes based or deriving from a changed or alternative logics of fabrication and even construction. This



aspect, the resulting innovative processes and manufacturing strategies, depict the most relevant aspect of this and similar projects, permitting the possibility of disciplinary advancement.

Merging the digital and the analogue has lead, in this specific case, to open ended processes, which can result in a new architectural sensibility, shifting the focus from the often prioritised question of shape to the intricate relation network between form, material, process and experiment. Experimenting at the intersection between established craft techniques —tailoring and concrete casting— and digital technologies —3D printing, patterning— has lead to the development of complex hybrid material system, resulting in a novel design and fabrication strategy which could be generically named ‘Digital Concrete’.

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